Holocene morpho-stratigraphic evolution of a compound submarine deltaic system in front of the shelf-incising Almanzora and Garrucha canyons (Palomares margin, southeastern Iberia)

D. Casalbore^{1,2}, M. Biancone², D. Casas³, P. Mata⁴, B. Alonso³, G. Ercilla³, F.L. Chiocci¹, P. Bárcenas⁵, N. López-González⁵

Affiliations

1 Dipartimento di Scienze della Terra, Università Sapienza di Roma, Piazzale Aldo Moro 5, 00185, Rome, Italy

2 Istituto di Geologia Ambientale e Geoingegneria, Consiglio Nazionale delle Ricerche, Piazzale Aldo Moro 5, 00185, Rome, Italy

3 Institut de Ciències del Mar-CSIC. Passeig Marítim de la Barceloneta 37-49. 08003 Barcelona, Spain

4 Instituto Geológico y Minero de España (IGME), Ríos Rosas 23, 28003 Madrid, Spain

5 Instituto Español de Oceanografía, Centro Oceanográfico de Málaga, Puerto Pesquero s/n, 29640 Fuengirola, Málaga, Spain

Abstract

The Holocene morpho-stratigraphic evolution of a compound submarine deltaic system linked with the Antas and Almanzora Rivers on the narrow (< 5 km) shelf along the Palomares margin (southeastern Iberia) has been reconstructed from the integrated analysis of geomorphology, seismo-stratigraphy and sedimentology. The shelf morphology is characterized by a 3-4 km wide deltaic body off the Almanzora River, where seafloor undulations and gullies are present. Larger and more incised gullies, crescent-shaped bedforms and pockmarks are recognizable at or close to the head of shelf-indenting canyons associated with the Almanzora-Garrucha canyon system.

The seismo-stratigraphy displays a strong and irregular basal reflector overlain by a sedimentary wedge, showing variable thicknesses (1-25 m) and seismic characteristics along and across the shelf. The main depocenter of this wedge is not located off the Almanzora River mouth (i.e., the main sedimentary input in the study area) but along the southern shelf encompassing the Almanzora and Antas rivers. Grain-size and sand compositional analyses show that silty sand with high terrigenous content (mostly quartz and mica) is mainly found on the submarine deltaic body. In contrast, sandy silt with variable ratios between terrigenous and biogenic contents is retrieved from the canyon head and associated gullies as well as from the surrounding mid-outer shelf.

The evolution of the Antas-Almanzora compound delta has been divided into three evolutionary stages, mainly driven by the interplay between paleo-topography and riverine and marine processes and modulated by sea level changes during the Holocene. The origin of the present-day morphological

features is also discussed, again highlighting a complex interaction between sedimentary gravity flow (mainly flash flood-generated hyperpycnal flows), storm-waves and shelf currents, fluid seepage and retrogressive slope failures.

Keywords

Hyperpycnal flows, hypopycnal flows, bedforms, sediment supply, prodelta, gullies, western Mediterranean

1 Introduction

In the last few decades, the growing collection of high-resolution seafloor imagery (multibeam bathymetry and backscatter mosaics), seismic profiles and seafloor sampling in shallow-water areas has largely increased our knowledge of the main erosive and depositional processes controlling the dispersal of riverine flows into the sea, as well as the morphological evolution of submarine deltaic systems (e.g., Ercilla et al., 2010; Urgeles et al., 2011; Hughes-Clarke, 2016; Bárcenas et al., 2017; Kostic et al., 2019; Trincardi et al., 2020). The location and the main geomorphological parameters (i.e., size and characteristics of the drainage basin, climate, water discharge, and sediment load) of the alluvial feeder systems are the main factors controlling the sediment input to the coastal area and shelf depocentres (e.g., Swift and Thorne, 1991; Mulder and Syvitsky, 1995; Olariu and Steel, 2009). On the other hand, the morphology of the continental shelf (shelf width and occurrence of shelf-incising canyons) along with the main oceanographic processes (i.e., shelf currents, storms and internal waves) tends to redistribute the riverine sediments along and across the shelf, leading to sediment transport gradients and contributing to the formation/preservation of geomorphic features on the shelf (Fagherazzi and Overeem, 2007; Gamberi et al., 2014). In particular, Mediterranean shelves are often narrow and morphologically characterized by small deltaic systems linked with short and steep rivers, draining tectonically controlled coastal ranges (Díaz and Ercilla, 1993; Fernandez-Salas et al., 2015; Chiocci and Casalbore, 2017). These rivers are typically characterized by extreme yearly variations in discharge, resulting in dry beds in summertime and winter floods with values up to several hundred m^3/s during short and severe rainy periods (e.g., Sabato and Tropenao, 2004; Lique et al., 2005). During these meteorological events, widespread small-scale mass-wasting events are triggered in the river watershed, dramatically increasing the solid/liquid discharge ratio and promoting the formation of hyperpycnal flows once they reach the coast (e.g., Milliman and Syvitski, 1992; Mulder and Syvitski, 1995; Syvitsky and Kettner, 2007; Casalbore et al., 2011). These submarine deltaic systems show, in fact, intermediate characteristics in terms of size, slope gradients, frequency of hyperpycnal flows, and grain-size between the large-scale, fine-grained deltas and the

small-scale, coarse-grained fan deltas (Barcenas et al., 2015). The internal architecture of these deltaic systems is typically characterized by sigmoidal wedge-shaped clinoforms. They have gently-sloping topsets mainly reworked by storm-waves and relatively steep foresets (corresponding to the prodelta slope), largely affected by seafloor undulations and less often by narrow gullies (Fernández-Salas et al., 2007; Urgeles et al., 2011; Barcenas et al., 2015; Gamberi et al., 2015; Casalbore et al., 2017). In this study, we show for the first time an integrated morphological, sedimentological and seismic analysis of the narrow continental shelf (< 5 km) encompassing the Antas and Almanzora Rivers on the Palomares margin (southeastern Iberia). Both rivers have been historically affected by several catastrophic flash floods, leading to the transport of high sediment yields and the formation of hyperpycnal flows at their river mouth (Capel-Molina, 1987; Sánchez García et al., 2016). Most of the riverine sedimentary supply is redistributed along the narrow shelf by the prevalent southward longshore drift and shelf current affecting this area or funnelled downslope within the Almanzora and Garrucha shelf-incising canyons (Puig et al., 2017). The overall goal of the paper is to reconstruct the morpho-stratigraphic evolution of the study area during the last sea level rise, with particular reference to the characterization of the most recent erosive-depositional processes that are currently controlling shelf sedimentation. With this reconstruction, we aim to better understand the interplay between a rough paleo-topography inherited by shelf-indenting canyons and associated paleo-valleys, riverine and marine processes in controlling the formation of the Almanzora-Antas compound submarine deltaic system and associated bedforms, i.e., seafloor undulations oriented parallel to the isobaths, different types of cross-shelf gullies, coaxial trains of crescent-shaped bedforms and pockmarks. The results of this study highlight the need for an integrated morpho-bathymetric, seismo-stratigraphic and sedimentological analysis of compound deltaic systems for proper classification within the scheme recently proposed by Bárcenas et al. (2015) for deltaic systems linked with short and steep rivers. Moreover, these results provide useful insights for a better understanding of the sink-to-source system of shelf-incising canyon heads facing “dirty” rivers (sensu Mulder and Syvitski, 1995), where hyperpycnal flows can impact offshore infrastructures and/or the funnelling of pollutants and marine litter in deep water (e.g., Tubau et al., 2015; Casalbore et al., 2018; Gerigny et al., 2019; Pierdomenico et al., 2019).

2 Regional setting

Geological/tectonic setting: The study area is located on the Palomares continental margin (southwestern Mediterranean), which is a Serravallian NNE-SSW margin located southeast of the Iberian Peninsula in the Gulf of Vera (Fig. 1a). The onland area is structurally dominated by the

103 Aguilas Arc to the north (Fig. 1a), made up of a series of antiforms that form part of the Betic
 104 Cordilleras; active faults with a land-sea continuation, such as the Carboneras-Gata and Palomares
 105 fault zones, are also recognizable (CF and PF in Fig. 1a; Acosta et al., 2013; Perez-Hernandez et al.,
 106 2014; Gómez de la Peña et al., 2016). Moreover, the continental indentation of the Aguilas Arc
 107 produces a southeastward tectonic tilting of the whole land-sea region that may provoke changes in
 108 the steepness of the margin (Ercilla et al., 2019 a, b). The study area was characterized by coastal
 109 uplift during the Plio-Pleistocene, which formed a set of raised marine terraces (Zazo et al., 2003)
 110 and promoted the development of steep rivers draining the Betic Cordilleras (Harvey and Wells, 1987;
 111 Stokes and Mather, 2003; Lique et al., 2005).

112 *Climate and river discharge:* In the arid and semiarid regions of southern Spain, river discharge from
 113 these rivers is mainly seasonal and associated with episodic flash-flood events, commonly occurring
 114 during the autumn/winter months in coincidence with the passage of Atlantic fronts (Lique et al.,
 115 2005, Machado et al., 2011). From south to north, the main water courses in the study area are the
 116 Aguas, Antas and Almanzora rivers (Fig. 1); among them, the Almanzora River has the largest
 117 drainage system (2611 km² wide and 90 km long), has one of the steepest longitudinal profiles in the
 118 whole peninsula and is the only river to develop a morphologically recognizable prodeltaic body
 119 (Sanz et al., 2002; Puig et al., 2017). Historical analysis has revealed that the Almanzora River has
 120 been affected by 36 major floods since 1550, with the most catastrophic flood recorded in October
 121 1973, which had a discharge of 5600 m³/s (Capel-Molina, 1987; Sánchez-García et al., 2019).
 122 Analyses of flood magnitudes and related frequencies have shown how these extreme catastrophic
 123 events recur with a return period of 100 years, while minor events happen with a higher frequency,
 124 reaching 5 to 10 years for floods with 684 and 385 m³/s average discharges, respectively (Sánchez-
 125 García et al., 2019). The increasing urbanization that has affected the Almanzora watershed in the
 126 recent historical period has played a key role in changing the river dynamics. The intense sand-mining
 127 activity in the river channel that started in 1974, the channelling of the last 15 km strait and the
 128 building of the Cuevas del Almanzora dam in 1982 are all factors that contributed to a reduction in
 129 flood risk and a dramatic decrease in riverine discharge into the sea (Sánchez-García et al., 2019).

130 *Physiographic and morphological setting:* The facing continental shelf has a maximum width of 5
 131 km, and the shelf break is located at an average depth of 110 m water depth (mwd, hereafter), except
 132 between the Almanzora and Garrucha canyons, where it is shallower because of canyon indentation
 133 (Fig. 1; Puig et al., 2017). Specifically, the Garrucha canyon head is located very close to the coast,
 134 at approximately 10 mwd, attaining a maximum vertical incision of 580 m (Fig. 1; Puig et al., 2017).
 135 In contrast, the Almanzora Canyon has a head between 50 and 90 m on the outer prodelta of the
 136 Almanzora River and is less incised, with a maximum value of 380 m (Fig. 1). Along its path, the

137 Garrucha Canyon first joins at 870 mwd two tributaries fed by a network of gullies located just south
 138 of the Almanzora prodelta (Fig. 1b). At 1100 mwd, it joins the Almanzora Canyon and at
 139 approximately 1800 mwd joins the Alias Canyon, continuing downslope as a large and single trunk
 140 debouching into the Algero-Balearic basin (Acosta et al., 2013; Perez-Hernandez et al., 2014).
 141 In general, the shelf morphology is characterized by convex-seaward prodeltas facing the major rivers
 142 (i.e., the Almanzora River), laterally evolving to elongate infralittoral prograding wedges (IPW,
 143 Hernandez-Molina et al., 2000), the geomorphic feature with greatest continuity along this part of the
 144 Iberic margin (Fernandez-Salas et al., 2015). Erosional or tectonically controlled features (faults,
 145 step-like escarpments, and terraces) often characterize most of the mid and outer shelf, where
 146 sediment cover is low or totally absent. Postglacial deposits are, in fact, mostly restricted to small
 147 pro-deltaic deposits off the main fluvial inputs, while fine sediment transport towards the south
 148 coupled with the abrupt shelf configuration led to fine sediment capture by submarine canyons and
 149 its export towards deeper domains (Lobo et al., 2015).
 150 *Wave and tidal regime:* The shelf is wave-dominated, with prevalent NE and SW winds, which can
 151 generate significant wave heights (generally < 5 m) with wave periods of 6–7 s during storm events,
 152 representing one of the main mechanisms for sediment resuspension over the shelf (Puig et al., 2017).
 153 Durán et al. (2018) performed a statistical analysis of significant wave heights, periods, and directions
 154 over the 2006-2016 period at the Cape Palos wave buoy, located approximately 30 km north of the
 155 study area. This analysis evidenced that the highest waves, reaching a maximum wave height of 7.80
 156 m and associated peak period of 9.5 s, are mainly related to the ENE and SW directions. The
 157 maximum wave height is also in agreement with the results of Salvadori et al. (2020), who estimated
 158 significant wave heights up to 9 m and storm durations over 220 hours for a return period of 200 years
 159 in the study area based on multivariate sea storm hindcasting using two drifting wave buoys.
 160 The shelf circulation in the study area is controlled by wind-induced currents as well as by a
 161 geostrophic current that carries old Atlantic waters towards the southwest along the shelf break,
 162 flowing as part of the Northern Current (Millot, 1999). According to Puig et al. (2017), storm-waves
 163 along with the occurrence of a general southward coastal current can also generate a theoretical
 164 maximum longshore drift of 78.000 m³/year in the study area that is directed southwards.

166 **3 Data and methods**

167 The datasets used in this work include multibeam bathymetry, very high-resolution seismic profiles
 168 and surface sediment samples, mostly obtained by the Fauces project onboard the R/V Sarmiento de
 169 Gamboa during the 2017 and 2018 cruises. In detail:

170 The high-resolution bathymetric map of the study area (Fig. 1b) was obtained by merging the 5 m
171 grid size digital elevation model (DEM) of the continental shelf, obtained in 2000 with Simrad EM12
172 and provided by the Spanish Fishing General Secretary, with the 10 m grid size DEM acquired during
173 the 2017 and 2018 Fauces cruises on the continental slope. Fauces data were DGPS-positioned,
174 acquired with an Atlas Hydrosweep DS multibeam echosounder (working at 14.5 and 16 kHz) and
175 processed through Caraibes software.

176 Very high-resolution seismic records with a maximum penetration of < 200 m and a metric vertical
177 resolution were acquired with the parametric echosounder Parasound Parastore P-35 operating with
178 primary frequencies of 18 to 39 kHz during the 2018 cruise (Fig. 1b). The seismic data were converted
179 and imported as SEG-Y files into IHS Kingdom Suite™ software for visualization and interpretation.
180 A sound velocity of 1500 m/s was used for the time/depth conversion.

181 Forty-eight surface sediment samples were gathered in the study area using a Van Veen grab during
182 the 2018 cruise; they were collected from 28 to 293 m wd (Table 1) mainly along transects
183 perpendicular to the shelf (yellow points in Fig. 1b). Grain size analysis was performed at the Institute
184 of Marine Sciences of Barcelona using a Coulter LS230 laser particle size analyser (CLS) that
185 determines particle grain sizes between 0.4 and 900 µm as volume percentages based on diffraction
186 laws (McCave et al., 1986). All samples were quartered, freeze-dried and treated with 10% hydrogen
187 peroxide to remove organic matter prior to measurement. Textural statistical parameters according to
188 the methods of Folk and Ward (1957) were established using GRADISTAT (Blott and Pye, 2001)
189 and TRI-PLOT (Graham and Midgley, 2000) Excel spreadsheets, considering a silt-clay limit of 4
190 µm according to the widely used Udden–Wentworth grain-size scale.

191 The composition of the sand fraction in 36 samples was examined using a binocular microscope, and
192 300 grains/sample were counted to obtain statistically representative results. Grains were split
193 between terrigenous and biogenic components: the terrigenous component included quartz, mica,
194 lightweight and heavyweight minerals (considering a density threshold of 3.5 g/cm³), pyrite,
195 glauconite, rock fragments and others; the biogenic components included benthic and planktonic
196 foraminifera, ostracod, sponge, echinoid, bivalve, gastropod, serpulid, pteropod and others.

197 Following this compositional classification, different grain types representative of each type formerly
198 identified, were selected for analysis by scanning electron microscopy (SEM) and energy dispersive
199 X-ray spectroscopy (EDX) at Instituto Geológico y Minero de España to provide qualitative and
200 quantitative chemical and elemental compositions.

201 Statistical analysis was performed on grain size and sand fraction composition results using R 3.1.3
202 and Past3 software. These analyses consisted of principal component analysis (PCA) and K-means
203 cluster analysis. PCA is often used to reduce the dimensionality of large datasets by transforming a

large set of variables into a smaller set that still contains most of the information in the large set. K-means cluster analysis allows us to define relationships between samples and variables composing groups (called clusters) that share common characteristics, and their results are represented in a hierarchical diagram.

4 Geomorphology of the study area

4.1 General physiography of the continental shelf

The study area is characterized by a 2-5 km narrow continental shelf, with the shelf break located approximately 110 mwd north of the Almanzora River mouth and 60/80 mwd in the sector encompassing the Antas and Almanzora River mouths, where it is strongly indented by the Garrucha and Almanzora canyons (Fig. 1b). The shelf can be divided into three sectors (southern, central, northern) based on the different morphologies and bathymetric cross-sections (BC1 to BC3 in Fig. 2).

The southern sector (SS in Fig. 2) is characterized by an overall smooth morphology and convex cross-section (BC1), with the occurrence of a marked break-in-slope at approximately 15 mwd, 2 km from the shoreline. This break-in-slope is present all along the southern sector, dividing an upper, almost flat area (gradients of approximately 0.6° in Fig. 2b) from a steeper (gradients of 1.5° - 2.5° in Fig. 2b) seafloor downslope.

The central shelf sector (CC in Fig. 2) is dominated by a 3-4 km wide convex-seaward fan-shaped morphology off the Almanzora River mouth (and for this reason named Almanzora Fan, for details see section 4.2) and has an overall convex-upward cross-section (BC2). A break-in-slope is also present here, but it occurs at shallower depths (approximately 10 mwd) and shorter distances from the coast (1 km from the coastline). Moreover, it is characterized by a smaller curvature in cross-section with respect to the southern sector, dividing an almost flat area (gradients $< 0.7^\circ$), from a steeper and planar profile downslope (gradients of approximately 1° - 1.5° in Fig. 2b).

The northern sector (NS in Fig. 2) is instead characterized by a concave-upward cross-section (BC3), with slope gradients passing from 2° in the first 50 mwd to 0.3° at approximately 70-100 mwd. The shelf morphology is quite rough and is related to the occurrence of small-scale irregular ridges and elongated scarps aligned parallel to the coastline. These features mainly occur in the proximal (< 30 mwd) and distal parts of the shelf (> 70 mwd).

4.2 Morphological features

237 Different small- and medium-scale morphological features are recognizable in the central and
 238 southern shelf sectors. The medium-scale features include the Almanzora fan and the break-in-slope
 239 on the southern shelf (described in section 4.1), whereas the small-scale features are often
 240 superimposed on the previous ones, encompassing gullies, crescent-shaped bedforms, pockmarks,
 241 seafloor undulations and megaripples (Figs. 2, 3 and 4).

242 The *Almanzora fan* extends from the coast down to 80-100 mwd over an area of approximately 13
 243 km² (Figs. 2 and 3). In plan view, it is morphologically formed by two main coalescing and convex-
 244 seaward areas (labelled A and B in Figs. 2 and 3) that are largely affected by gullies and seafloor
 245 undulations (see below for details). Area A is mostly oriented along the NW-SE direction and
 246 terminates in correspondence with the Almanzora canyon head. Area B is oriented along the WNW-
 247 ENE direction and progressively fades out in the outer shelf. In the cross-section (BC2 in Fig. 2), the
 248 upper flat area (approximately 10mwd) of the fan is related to the topset of the Almanzora fan,
 249 whereas the steeper downslope surface can be associated with the prodelta slope, as testified by the
 250 available seismic profiles (Fig. 5).

251 *Gullies* are widespread in the study area and can be divided into two main types (Figs. 3 and 4) based
 252 on their location and morphology:

253 *Gully type 1* is recognizable offshore the Almanzora river mouth (Fig. 3); the morphometric
 254 characteristics of these gullies change alongslope. In the shallowest area (< 15 mwd), two U-shaped
 255 gullies are present, with a length of ~600-700 m, width of ~150-200 m, and depth incision of ~0.5-2
 256 m (BC4 in Fig. 4). At greater depths, a network of narrow gullies mostly occurs on the prodelta slope,
 257 oriented radially with respect to the Almanzora River mouth (Fig. 3). These gullies are ~300-2000 m
 258 long, ~20-40 m wide, and ~0.3-1.5 m deep (BC5 in Fig. 4). They tend to feather in the lowermost
 259 part of convex-seaward area B at depths greater than 60 m, where the shelf morphology becomes
 260 generally smooth and slope gradients decrease to values < 0.8° (Fig. 2). In contrast, in the lower part
 261 of convex-seaward area A, these gullies tend to converge within larger gullies (Fig. 3). These larger
 262 gullies develop just upslope of the Almanzora canyon head (Fig. 2a), where slope gradients markedly
 263 increase to values higher than 2° (Fig. 2b). They are ~300-900 m long, ~50-90 m wide, and ~5-20 m
 264 deep (BC6 in Fig. 4); their incision depth generally increases downslope. Small landslide scars, with
 265 diameters of a few hundred metres, are locally present in the upper part of these gullies (Figs. 3 and
 266 4).

267 *Gully type 2* is identified in the southern shelf, where they start to develop at depths greater than 50
 268 m from an overall smooth seafloor (Fig. 3). These gullies are mostly V-shaped erosive features, ~200-
 269 1500 m long, ~20-100 m wide, and 1-5 m deep (BC6 in Fig. 4). At depths greater than 80 m, they

270 converge in larger gullies linked with the tributaries of the Garrucha Canyon, where slope gradients
 271 markedly increase, similarly to what observed for the Almanzora Canyon.

272 *Crescent-shaped bedforms* (CSBs in Fig. 4) are recognizable mainly in the central sector, both within
 273 the larger gully's thalweg and (mainly) upslope of them, where they form within subtle gullies, being
 274 few tens of metres wide and some metres deep. These bedforms have wavelengths of some tens of
 275 metres and wave heights of a few metres; their crestlines are oriented parallel to the isobaths and
 276 display a stepped morphology in cross-section, with a gently sloping stoss side followed by a steep
 277 leeward side (BC7 in Fig. 4). Sometimes, semi-enclosed circular or downslope elongated depressions
 278 are observed at the base of the CSB's lee side (BC8 in Fig. 4).

279 *Pockmarks* are mainly concentrated in the central sector (Fig. 3) and are often aligned along the major
 280 gully thalweg and within small landslide scars recognizable at their heads (Fig. 4). The pockmarks
 281 are mainly subcircular depressions with an average diameter of 50 m and negative relief of a few
 282 metres (BC9 in Fig. 4), except for some pockmarks showing a downslope elongated shape.

283 *Seafloor undulations* are mainly located between 15 and 60 mwd on the Almanzora prodelta slope
 284 (Figs. 2 and 3). Moreover, they are locally present on the interfluvies between major gullies in the
 285 central and southern sectors of the shelf at depths greater than 50 m (Fig. 4). They have wavelengths
 286 of 40-130 m and wave amplitudes of some metres; their crestlines are roughly oriented parallel to the
 287 isobaths (Figs. 2, 3 and 4). In cross-section, they are often asymmetric downslope, with a longer and
 288 gently sloping stoss side followed by a shorter and steeper lee side (BC10 in Fig. 4), even if more
 289 symmetric shapes are also recognizable. Wavelengths tend to increase downslope, whereas wave
 290 heights have a more complex pattern, even if a general downslope decrease is often recognizable.

291 *Megaripples* are mainly located in the southern sector within the first 15 mwd over an almost flat
 292 seafloor (Figs. 3a and Fig. 1 ESM). They are formed by a series of sinuous and regularly spaced
 293 NNW-SSE ridges, with wavelengths of 70-100 m and heights of a few decimetres with respect to the
 294 surrounding seafloor (BC11 in Fig. 1 ESM).

296 **4.2 Seismo-stratigraphic characterization**

297 The parametric seismic profiles (see location in Fig. 1b) show the presence of an irregular and high-
 298 amplitude basal reflector (BR in Fig. 5) that commonly prevents penetration of the acoustic signal. In
 299 strike profiles, the BR is characterized by multiple paleo-incisions at different spatial scales (Figs. 5a,
 300 b and c). The larger paleo-incisions recognizable on the seismic profiles (Figs. 5a, b and c) match the
 301 present-day position of the type-2 gullies and tributaries of Garrucha Canyon (Figs. 1 and 3), as also
 302 shown by the isochrones of the BR (Fig. 6b). At a large spatial scale, the BR is generally well marked
 303 and deeper in the southern shelf sector, forming an overall depressed area, while it is shallower and

304 more difficult to image in the central shelf sector, below the Almanzora prodelta (Figs. 5a and b). In
305 dip profiles, the BR seems to unconformably cut clinoforms of the lower unit U2 that are barely
306 recognizable on the parametric profiles (Figs. 5e and f). Above the BR, seismic unit U1 is present,
307 displaying variable seismic facies (from semitransparent to medium-high-amplitude parallel
308 reflectors) and thickness (from a few metres to over 20 m), both along and across the shelf (Fig. 5).
309 Specifically, the isopach map (Fig. 6c) shows that U1 reaches the maximum thicknesses in the
310 southern sector (higher than 20 m), while it has an average thickness of approximately 10-12 m at
311 water depths of 40-50 m in the central sector, decreasing downslope towards the shelf break (Figs.
312 5d, e, f, and 6). In the northern sector, U1 is thin or completely lacking (Figs. 5 and 6c), justifying the
313 convex BC3 profile in Fig. 2.

314 Unit U1 is divided into three sub-units, namely, U1a, U1b, and U1c (from older to younger in Fig.
315 5), according to their external and inner geometries and seismic attributes, e.g., amplitude, lateral
316 continuity, and frequency of internal reflectors.

317 Sub-unit U1a is generally thin (a few metres) and patchy, commonly filling paleo-incisions of the
318 BR; it is characterized by semi-transparent facies and/or low-amplitude and sub horizontal reflections
319 (Fig. 5a). Sub-unit U1b has a variable thickness and seismic attributes between the central and
320 southern shelf sectors (Fig. 5). In the central sector, U1b has a thickness of some metres and generally
321 has semi-transparent facies, except for the northernmost sector of the prodelta, where low continuity
322 and medium-amplitude northeastward-dipping inner reflectors are recognizable (Figs. 5a, b). On the
323 southwestern shelf, U1b reaches a maximum thickness of 12 m and is characterized by high-
324 frequency and medium-amplitude reflectors generally dipping southward (Fig. 5a, b and c),
325 downlapping the BR or U1a when present; the amplitude of seismic reflectors progressively decreases
326 towards the southern shelf. Sub-unit U1c consists of sub-parallel, wavy or chaotic high-amplitude
327 reflectors and is found in all the areas encompassing the Almanzora prodelta and the Antas River,
328 with an average thickness of 4-7 m (Fig. 5).

329

330 **4.3 Sedimentological characterization**

331 4.3.1 Sediment textures

332 The Antas-Almanzora shelf is characterized by the dominance of two textures, namely, sandy silt and
333 silty sand, when plotted on the ternary diagram of Folk (1954, Fig. 7b). Silty sand is represented by
334 two granulometric fractions, fine sand and very fine sand, while sandy silt is represented by coarse
335 silt and medium-fine silt.

336 *Fine sand* samples (Fig. 7) are limited to the shallowest part of the Almanzora prodelta; these samples
337 are poorly sorted, very fine skewed and very leptokurtic (Table 3).

338 *Very fine sand* samples (Fig. 7) are mostly observed in the Almanzora prodelta affected by seafloor
339 undulations and type-1 gullies, and in the shallowest part of the southern shelf. All these samples are
340 poorly sorted, very fine skewed and leptokurtic/very leptokurtic (Table 3).

341 *Coarse silt* samples (Fig. 7) mostly occur in the upper part of type-2 gullies and just upslope of the
342 Almanzora Canyon head, except for a few samples located along the northern mid-shelf. These
343 samples are poorly sorted, fine and very fine skewed, and platykurtic/mesokurtic (Table 3).

344 *Medium-fine silt* samples (Fig. 7) are mainly located in the type-2 gullies and downslope tributaries
345 of the Garrucha canyon. These samples are poorly sorted, fine skewed to symmetrical and coarse
346 skewed and mesokurtic (Table 3).

347 4.3.2 Sand compositional analysis

348 The sand compositional analysis (Tables 4 and 2 ESM) shows that samples are generally dominated
349 by terrigenous particles (between 63% and 98%). Terrigenous components include mainly mica (17-
350 53%, Fig. 8e) and quartz (9-40%, Fig. 8c), followed by lightweight (6-29%) and heavyweight (3-
351 20%) minerals. Among the micas class, the main minerals identified were biotite, muscovite (often
352 altered by haematite and Fe-oxides), phlogopite, paragonite and margarite-vermiculite. The main
353 lightweight minerals are K-feldspar, albite, calcite and dolomite, while the heavyweight minerals are
354 ilmenite, rutile, haematite, Fe-Ti oxides, and amphiboles such as kaersutite, glaucophane and
355 hornblende. Pyrite and glauconite categories have negligible percentages (< 1%), as well as rock
356 fragments (0-8%, average of 2%, Figs. 8a and d), i.e., aggregates composed of epidote, quartz,
357 muscovite and other heavyweight minerals. In terms of the biogenic content (2-37%, Table 3), benthic
358 foraminifera (both whole and broken tests, Fig. 8b) and heterogeneous fragments of bivalves,
359 ostracods (Fig. 8f), sponge spicules and even echinoids were prevalent; they were found at all water
360 depths. In contrast, planktonic foraminifera (Fig. 8b) are mainly limited to the deepest samples within
361 the tributaries of the Garrucha Canyon.

362 4.3.3 Statistical (PCA) analysis

363 The PCA performed on the 36 samples and 9 variables (textural and compositional parameters)
364 identified three main principal components (PCs) explaining 98.07% of the total variance (Fig. 9b).
365 PC 1 (81.46% of the variance) is defined by textural parameters, showing a negative correlation
366 between silt and sand. PC 2 (11.98% of the variance) is defined by the sand composition, indicating
367 a negative correlation between terrigenous and biogenic components. PC 3 (4.63% of the variance)
368 is defined by a negative correlation between quartz and mica contents. The samples are grouped by
369 cluster analysis into 5 groups, and the results are shown in Fig. 9c.

370 *Group 1* is delineated by a sand texture (62-87% in Table 4), with a mean grain size of 63-166 μm .
371 The sand fraction is dominated by a terrigenous composition (> 93%, Table 4), most of which is

372 associated with quartz (between 25 and 40%) and mica (17-42%) contents. These samples (Fig. 9a)
373 are mostly retrieved from the undulation field off the Almanzora River, except for sample DC14,
374 which is located on the shallowest part of the southern shelf and shows characteristics (lowest quartz
375 content and high mica content) like those of group 2.

376 *Group 2* is also delineated by sand textures, but with a lower percentage of both sand (43-48%) and
377 mean grain size value (44-49 μm) than samples from group 1 (Tables 4 and 2 ESM). The sand fraction
378 is likewise dominated by terrigenous content (above 92%), with mica (26-53%) being more abundant
379 than quartz (14-34%). Samples of this cluster (Fig. 9a) are located outside the undulation field, both
380 on the inner/mid-shelf and in the upper parts of type-2 gullies; this group is the buffer between groups
381 1 and 3.

382 *Group 3* is formed by silt-dominated samples (silt content between 58 and 80%), with the mean size
383 ranging between 17.8 and 34 μm . The sand fraction is still dominated by a high terrigenous content
384 (from 86 to 97%), with a mica-dominated composition (26-51%) and lower quartz content (19-33%).
385 These samples (Fig. 9a) were mainly retrieved from the type-2 gullies. DC18 is the deepest sample,
386 having the highest clay (9%) and biogenic content (14%) of group 3 (Table 2 ESM), which makes it
387 more comparable to samples DC47 and DC48 from group 4 (Fig. 9b).

388 *Group 4* is also formed by silt-dominated sediments (silt content of 65-81%), with mean grain sizes
389 ranging between 14.8 and 31 μm . This group has a higher biogenic content (18-33%) than group 3;
390 its terrigenous content is dominated by micas (29 to 44%) and quartz (9 to 21%). These samples are
391 the deepest (> 130 mwd) and retrieved within the Garrucha tributaries (Fig. 9a), except for DC43,
392 which was collected from the northern mid-shelf, showing features similar to samples DC42 and
393 DC50 of group 5 (Table 2 ESM).

394 *Group 5* is characterized by a few silt-dominated samples (silt content of 51-64%), with a mean grain
395 size of 24-41.6 μm (Table 4). These samples show the highest biogenic content among all the groups,
396 ranging from 22 to 37%. Samples DC42 and DC50 are located on the northern shelf, outside of the
397 undulation field. The DC19 sample is instead found in the lower part of a type-2 gully, but it has a
398 lower biogenic content, which is more comparable to the surrounding fine-grained samples of groups
399 3 and 4.

400

401 **5 Discussion**

402 The integration of multibeam bathymetry, seismic profiles and sedimentological data allows us to
403 reconstruct both the morpho-stratigraphic evolution of the shelf encompassing the Antas and
404 Almanzora Rivers during the last sea level rise (5.1) and the key processes acting presently and

controlling the development of the current main bedforms, i.e., gullies, crescent-shaped bedforms, pockmarks and seafloor undulations (5.2).

5.1 Chronostratigraphic and paleo-environmental interpretations

The seismo-stratigraphic setting of the Antas-Almanzora shelf is quite similar to that observed in the nearby northern shelf of the Alboran Sea (Ercilla et al., 1992 and 1994; Ercilla and Alonso, 1996), as they share the same hinterland geology (i.e., the Betic Cordilleras) and sedimentary sources (i.e., mainly steep and short rivers with torrential regimes and coastal erosion) (Fernández-Salas et al., 2015a). According to such studies, the basal reflector observed in seismic profiles (BR in Fig. 5) is thought to have formed during subaerial erosion due to glacio-eustatic sea level fall and subsequent Holocene reworking, thereby forming a wave ravinement surface. This interpretation is consistent with the fact that this reflector unconformably cuts underlying clinoforms (barely recognizable in dip seismic profiles) in the middle and outer shelf, similar to what was observed in other Mediterranean shelves (e.g., Chiocci, 1994; Lobo and Ridente, 2014; Fernandez-Salas et al., 2015b). A similar high amplitude basal reflector was also identified on the Murcia shelf, 30 km north of the study area, and similarly interpreted as a Holocene ravinement surface by Durán et al. (2018).

By assuming that the BR corresponds to the wave ravinement surface reworked during the last transgression, the overlying sedimentary cover (U1 in Fig. 5) can be interpreted as mostly Holocene in age. This interpretation is also supported by its thickness (< 25 m), which is comparable to that reconstructed for a similar Holocene unit recognized in the nearby, northern Alboran shelf (e.g., Ercilla and Alonso, 1996; Lobo et al., 2006). Three evolutionary stages (1, 2, 3) of the Antas-Almanzora shelf during the Holocene were reconstructed based on the geometry and seismic attributes of sub-units U1a, U1b, and U1c (Fig. 5).

Stage 1-The paleo-incision infilling stage is mostly limited to the filling of paleo-incisions (U1a in Fig. 5), interpreted as ancient river valleys linked with the head of the shelf-incising Almanzora and Garrucha canyons (Fig. 6b; Puig et al., 2017). This filling is likely due to the trapping of riverine material during the last late low stand-early transgression, similar to what was observed on other shelves elsewhere (e.g., Corradi et al., 1984; Chiocci and La Monica, 1996; Tortora et al., 2001, Conti and Furtado, 2009; Durán et al., 2018, Hepp et al., 2019).

Stage 2-The early Almanzora prodelta stage is mainly associated with U1b (Fig. 5). During this stage, the southern shelf acted as a main depocenter (thickness up to 12 m) because this area was structurally more depressed with respect to the central/northern shelf, where the Betic Cordillera reaches the coast just north of the present Almanzora River mouth (Fig. 1a), and it may locally sub-outcrop on the northern shelf (BC3 in Fig. 2). During this stage, the southern shelf was progressively filled with sediments mostly sourced from the Almanzora River, as suggested by the overall southward dipping

439 of seismic reflectors within U1b (P1 in Fig. 5a). This is also supported by a general decrease in the
440 seismic amplitude of these reflectors from the Almanzora prodelta towards the south, which could be
441 related to an overall decrease in sandy sediment moving away from the source area, i.e., the
442 Almanzora River mouth. At that time, the Almanzora River mouth was possibly in an inner position,
443 where today there is a Holocene coastal plain with an average thickness of 10 m
444 (http://info.igme.es/cartografiadigital/datos/magna50/pdfs/d10_G50/Magna50_1015.pdf),
445 supporting the inference that only fine-grained sediments could reach the southern shelf. The
446 mechanism responsible for this sustained southward transport of fine sediments can be associated
447 with the diversion of the Almanzora riverine plume by the prevalent shelf currents (Fig. 11 and section
448 2), similar to what was observed for the present-day grain size distribution of samples retrieved in the
449 study area (Fig. 7 and section 5.2). The prevalence of long term south-westward alongshore sediment
450 transport along this part of the Iberian margin during the Holocene is also supported by the
451 morphology and internal architecture (i.e., south-westward dipping oblique reflections) of sand ridges
452 and superimposed dunes recognized between 58 and 78 mwd on the Murcia shelf (Durán et al., 2018).
453 In the same study, repeated bathymetric surveys also show a southwest migration of sand waves over
454 a time span of 10 years, indicating ongoing activity of this current.

455 *Stage 3-The late Almanzora prodelta stage* is associated with U1c (Fig. 5) and mainly records the
456 emplacement of coarser-grained sediments fed by the Antas and Almanzora Rivers, as suggested by
457 high-amplitude, wavy and chaotic reflectors characterizing this upper seismic unit and the high values
458 of mean grain size from seafloor sampling (Fig. 7, Table 4 and 1 ESM). Once the difference in height
459 between the central and southern sectors was partially levelled by U1b and possibly, sea level
460 stabilized at its present highstand level, coarse-grained sediments from the Almanzora (mainly) and
461 Antas rivers are able to prograde on the shelf. As a whole, U1c looks quite similar to the upper seismo-
462 stratigraphic interval observed in many Mediterranean prodeltas, often associated with the present
463 highstand system tract (e.g., Urgeles et al., 2011; Lobo et al., 2015; Casalbore et al., 2017). However,
464 we are aware that the limit between highstand and transgressive system tracts is often transitional in
465 such settings (Fig. 5) and difficult to define unambiguously in the absence of core data. In addition
466 to sea level changes, climatic conditions and riverine dynamics can change the sediment supply over
467 time, explaining the vertical and lateral variability in amplitude, continuity and geometry of seismic
468 reflectors, as observed in the study area.

469 Based on the above stratigraphic reconstruction, the submarine deltaic system linked to the
470 Almanzora River is much larger than the morphological limit of the Almanzora fan recognizable from
471 bathymetry (Fig. 3), overlapping in space and time with the nearby submarine deltaic system of the
472 Antas River and thus forming a compound system. This is different from several submarine deltaic

473 systems described in the literature in the Mediterranean Sea (e.g., Urgeles et al., 2011; Bárcenas et
474 al., 2015 and references therein, Gamberi et al., 2014; Casalbore et al., 2017), where these
475 sedimentary bodies are typically associated with a single river mouth. To date a similar compound
476 delta has been previously described for the Fluviá, Muga and Ter prodeltas in the NW Mediterranean
477 (Díaz et al., 1993; Ercilla et al., 1995). The recognition of compound systems has implications for the
478 recent geomorphological classification of submarine deltaic geometries linked to steep, mountainous
479 drainage basins proposed by Bárcenas et al. (2015), where three basic types of plan view distributions
480 have been identified according to their length-to-width ratios: elongate, linguoid and lobate. In the
481 study area, the real Almanzora-Antas submarine deltaic system is markedly more elongated than its
482 present-day morphological expression, highlighting the need for a detailed seismo-stratigraphic
483 characterization of the submarine deltaic systems and surrounding shelf for its classification. A proper
484 classification of the submarine deltaic system is of high importance because it can provide insights
485 into different parameters of the alluvial feeder system and receiving basin, such as the average river
486 discharge and sediment loads, flow velocity and slope, lateral transport of sediment, coastline distance
487 and water depth of the offlap break (Bárcenas et al., 2015).

488 Within the Almanzora-Antas compound deltaic system, the morphologically recognizable Almanzora
489 fan can be mainly considered the result of hyperpycnal flows sourced by the Almanzora River (Fig.
490 11) because:

491 1) The coexistence of a radial network of gullies and seafloor undulations (Figs. 2 and 3) is commonly
492 associated with the interaction of these sedimentary gravity flows with the seafloor (Gamberi et al.,
493 2015; Casalbore et al., 2017; Kostic et al., 2019), as also discussed in sections 5.2 and 5.3.

494 2) The high-amplitude and chaotic upper seismic facies (U1c in Fig. 5) is similar to that found in the
495 upper part of other submarine deltaic architectures linked with short and steep rivers, where
496 hyperpycnal flows play a major role in its evolution (Urgeles et al., 2011; Lobo et al., 2015).

497 3) The coarse-grained samples with high terrigenous content (group 1 in Fig. 9) are indicative of high-
498 energy events with a clear riverine signature.

499 In contrast, the shallow and nearby domains of the compound deltaic system are not affected as
500 directly or strongly by hyperpycnal flows, as suggested by the presence of a large megaripple field
501 developed over a marked break-in-slope on the southern shelf (Figs. 2, 3 and Fig. 1 ESM), interpreted
502 as the edge of an infralittoral prograding wedge, a feature commonly observed along this part of the
503 Iberian margin (Fernandez-Salas et al., 2015). Both morphological features clearly point out a main
504 control of the storm waves in these domains, reworking the sediments transported by the Almanzora
505 and Antas Rivers or produced by coastal erosion, similar to what was observed in the El Masnou
506 infralittoral sedimentary environment in Catalonia (Ercilla et al., 2010).

507

508 **5.2 Formation and origin of the bedforms**

509 **5.2.1 Typifying the continental shelf gullies**

510 This work offers a unique opportunity to make progress in gully interpretation by allowing the
511 identification of two main categories: *deltaic*- and *storm wave-related gullies* (Fig. 10) based on their
512 location, morphological/sedimentological features and formative process.

513 *Deltaic-related gullies* are located offshore the Almanzora river mouth (type 1 in Figs. 3, 4 and 10)
514 and mainly ascribed to the activity of flood-related hyperpycnal flows generated by this river. The
515 Almanzora River is historically susceptible to intense and recurrent flash-flood events during which
516 large amounts of sediment are rapidly transported into the sea (Sánchez-García et al., 2019 and
517 reference therein). In the topset area (< 15 mwd) of the Almanzora fan, the recognition of two gullies
518 with U-shaped morphology (BC4 in Fig. 4 and Fig. 10b) and relatively high width (200 m),
519 approximately matching the width of the Almanzora River mouth, strongly supports their
520 interpretation as result of the scouring of rip and undertow currents and/or hyperpycnal flows formed
521 during river floods (e.g., Díaz and Ercilla, 1993; Hughes Clarke et al., 2014; Mitchell, 2005;
522 Casalbore et al., 2017). Moreover, recent studies on the Squamish and Fraser prodeltas indicates that
523 such gullies could be formed or reworked by hyperpycnal flows triggered by settling process from
524 hypopycnal river plume (e.g., Hage et al., 2019; Hill and Lintern 2021). Even if no samples are collected
525 on these gullies, they are likely floored by sandy sediments, as indicated by seafloor samplings and
526 backscatter mosaics used for mapping the Spanish continental shelf, Sheet MC047-Garrucha, within
527 the ESPACE Project (Sanz et al., 2002).

528 After their formation, these gullies would remain active and enlarge by acting as preferential conduits
529 for subsequent sedimentary gravity flows, as suggested by their downslope evolution in a radial
530 network of narrow and subtle gullies occurring on Almanzora prodelta (Figs. 3 and 10), similar to
531 what was recognized off other prodeltaic deposits linked to short and steep rivers elsewhere (Chiocci
532 and Casalbore, 2011; Hill et al., 2012; Gamberi et al., 2015; Martorelli et al., 2016; Casalbore et al.,
533 2017). These gullies are likely ephemeral features during prodeltaic system evolution, as supported
534 by difficulties in their recognition in shelf stratigraphy through the available seismic profiles (see, for
535 instance, P1 in Fig. 5a). Indeed, this type of gully is not commonly reported in other Mediterranean
536 prodeltas linked to steep and short river courses (e.g., Urgeles et al., 2011; Bárcenas et al., 2015; Lobo
537 et al., 2015), except for the few examples previously mentioned. The presence/absence of such gullies
538 could depend on several factors, such as differences in data resolution and/or in the erosive capacity
539 of hyperpycnal flows along different prodelta slopes due to variable flow properties (e.g.,
540 concentration, grain size, and velocity), seafloor type and local slope gradients. In the study area,

slope gradients seem to play a major role in the formation of such gullies, mainly considering the relatively higher slope gradients (1° - 1.5°) characterizing Almanzora prodelta, which are comparable to those measured on Mazzarrà prodelta in the Gulf of Patti, where similar gullies were observed (Casalbore et al., 2017). Moreover, we cannot exclude the role of sedimentary gravity flows generated by submarine small-scale slope failures on the topset-prodelta slope in the formation of these gullies. This is suggested by the recognition of a slide scar just below the rollover point of the delta (Fig. 3); similar processes have already been documented in other deltaic systems (e.g., L'Heureux et al., 2010; Clare et al., 2016; Trincardi et al., 2020), mainly triggered during severe storm-waves (e.g., Henkel, 1970; Obelcz et al., 2017; Wang et al., 2020). In both cases, the main contribution of riverine material in the gully formation is supported both by the coarsest-grained textures (mostly silty sand, represented by green and blue dots in Fig. 7) and prevalent terrigenous content (especially quartz and micas; group 1 in Fig. 9a and Table 4) of samples retrieved from the prodelta slope.

The gullies affecting the Almanzora prodelta can feather downslope in the outer shelf (B sector in Figs. 2 and 3) or merge into larger gullies when associated with a marked increase in slope gradients at the head of the shelf-incising Almanzora canyon (A sector in Figs. 2 and 3). This break-in-slope triggers an increase in erosive activity of sedimentary gravity flows from the shelf, such as the ignition of erosive turbidity currents (Parker, 1982), leading to a progressive increase in gully incision downslope (Figs. 3, 4 and 10). However, the first evidence associated with this increase in erosive power of the flows is witnessed by the recognition of coaxial trains of CSBs just upslope of the canyon head (Fig. 4). These features are similar in size and morphology to those recognized in the distal part of other prodeltas (Kostic et al., 2019) or within active canyon heads (e.g., Paull et al., 2010; Babonneau et al., 2013; Casalbore et al., 2020), where they have been interpreted as transitional upper-flow-regime bedforms or cyclic steps, i.e., a class of upslope-migrating bedforms generated in response to Froude-supercritical flow (Kostic, 2011). These bedforms are considered an important mechanism for the initiation of channelized features (e.g., Covault et al., 2014; Vendettuoli et al., 2019), scouring the seafloor and forming shallow “proto-gullies” evolving downslope in larger gullies. It should also be considered that the enhanced erosive activity of sedimentary gravity flows at the canyon head can also favour the development of retrogressive instability processes, as testified by the occurrence of small landslide scars at the head of the larger gullies (Fig. 4). Available sediment samples from these gullies show the presence of sediments with high terrigenous content (groups 1 and 2 in Fig. 9, Table 4 and 2ESM), again indicating a riverine origin (Fig. 7, Table 1 ESM).

According to Puig et al. (2017), in the Antas-Almanzora shelf, the formation of both coaxial trains of bedforms and larger gullies could have also been favoured by widespread pockmarks recognized in the area (Figs. 3 and 4). These pockmarks have been previously linked to seepage and groundwater

sapping through coarser and more permeable sedimentary units within the Almanzora prodeltaic deposits (Puig et al., 2017) because clear clues of free gas acoustically masking seismic reflectors are not found in the available profiles, as supported by the analysis of the new seismic profiles collected for this study (apart from a few small areas, where acoustic masking could be locally recognizable). More generally, available data suggest a complex interaction between vertical fluid migration and the formation of pockmarks, small-scale instabilities, crescent-shaped bedforms and gullies that deserves the collection of further data and analyses to be fully understood.

Storm wave-related gullies are limited to the southern shelf just upslope of the tributaries of the Garrucha canyon (Figs. 3, 4 and 10), and their origin is puzzling because they seem to be disconnected from the present-day Almanzora River mouth and associated deltaic deposit (purple dashed line in Figs. 3 and 10). A similar configuration is reported for relict gullies recognized off the Tiber River (Chiocci and Normark, 1992). However, seismic profiles show that these gullies are active erosive lineaments carving the upper seismic sub-unit U1c (P2 and P3 in Fig. 5), similar to the type-1 gullies analysed thus far. A possible explanation for the formation of this type of gully is related to the development of “distal and off-axis hyperpycnal flows” generated by convective fingering and rapid settling of particles from the Almanzora hypopycnal sediment plume during and following the main flood events (Parsons et al., 2001; Clare et al., 2016; Puig et al., 2017), especially if coupled with severe storm waves (Ogston et al., 2000; Wright and Friedrichs, 2006). In the study area, riverine plumes generated by the Almanzora River can preferentially deviate southward from the prevailing shelf currents (Fig. 10). Once the plumes reach the head of the Garrucha Canyon tributaries, they may be destabilized and start to finger due to the centrifugal force acting on such unconfined flows when they pass over a break-in-slope, as suggested by models of Parson et al. (2007) and Fedele and Garcia (2009). This inference is supported by the convergent pattern of gullies present here, similar to what was proposed by Pratson et al. (1994) for the gullies developed on the New Jersey continental slope as well as by the development of such gullies in correspondence with an increase in slope gradients at or close to the shelf-indenting canyon head. The break-in-slope also promotes the ignition of sedimentary gravity flows downslope, increasing their erosive capacity as testified by the downslope increase in size and depth channel of gullies within the Garrucha tributaries, similarly to what observed for deltaic-related gullies within the Almanzora Canyon head.

Sediment samples from the upper and subtle gullies are characterized by silt-dominated textures (Fig. 7), with high terrigenous content (group 3 in Fig. 9a and Table 4), again reflecting a main riverine contribution, even if more distal from the source area. In contrast, samples from the downslope tributaries of Garrucha Canyon are characterized by fine-grained textures (Fig. 7) but with a marked

608 increase in biogenic content (group 4 in Fig. 9 and Table 4), indicating a larger influence of
609 hemipelagic sedimentation and/or by-pass of hyperpycnal flows.

610

611 ***5.2.2 Deciphering the formation of seafloor undulations over the Almanzora prodelta***

612

613 Seafloor undulations are mainly developed over the prodeltaic deposits linked with the Almanzora
614 River (Figs. 3 and 4), and they are similar in size and morphology to the undulations observed in
615 several Mediterranean prodeltas (Urgeles et al., 2011), whose origin remains unclear and is subject
616 to long-lasting debate. Seafloor undulations have been alternatively interpreted as creep or early
617 incipient instability (e.g., Díaz and Ercilla, 1993; Chiocci et al., 1996; Lykousis et al., 2003), sediment
618 waves induced by bottom currents, internal waves and/or hyperpycnal flows (e.g., Urgeles et al.,
619 2007; Lobo et al., 2015), or a combination of both deformation and sedimentary bedforms (e.g.,
620 Cattaneo et al., 2004; Marsset et al., 2004; Sultan et al., 2008). In the study area, our preferred
621 interpretation is that of sediment waves related to sedimentary gravity flows (i.e., mainly flood-
622 generated hyperpycnal flows), because of the following reasons: a) the Almanzora River is able to
623 generate frequent hyperpycnal flows, as suggested by its steep course and torrential regime, as well
624 as by a record of severe floods in historical times (see section 2); b) the coexistence of seafloor
625 undulations and narrow prodeltaic-related gullies on the Almanzora prodelta, the latter previously
626 interpreted as the trace of hyperpycnal flows; c) the crestlines of seafloor undulations are oriented
627 parallel to the isobaths, hindering an oceanographic explanation (unless to envisage the breaking of
628 internal waves, as suggested by Urgeles et al., 2011) and highlighting a main role of gravity-driven
629 processes; d) the seafloor undulations are mostly limited to the present-day Almanzora prodelta
630 (purple dashed line in Fig. 3); and e) available seafloor sampling from the undulations area shows
631 sandy textures with high terrigenous content (groups 1 and 2 in Fig. 9a and Table 4), indicative of a
632 riverine source with respect to the surrounding samples (DC42, 43, 50 in Fig. 9a and Table 2 ESM),
633 where the biogenic content markedly increases to 37%. We tend to exclude a major role of creep
634 processes in the study area because similar or more suitable conditions for its development would be
635 present in the southern shelf, which is still part of the submarine deltaic system (as discussed in section
636 5.1), but it is characterized by higher sedimentary thicknesses, a steeper seafloor (Fig. 2b) and finer-
637 grained sediments (Fig. 5a and Table 1 ESM). Nevertheless, no evidence of such seafloor undulations
638 is found on the southern shelf, except for a few bedforms on the gully interfluvies. Regardless, we are
639 aware that a more detailed morphometric analysis of the undulations (such as that performed by Lobo
640 et al., 2015 on the Guadalfeo prodelta) along with their seismic and geotechnical characterization
641 would be required to better constrain their formation, but this is beyond the scope of this paper.

642 Similarly, detailed oceanographic surveys are required to better understand the possible role of
643 internal waves in the genesis of undulations.

644

645 **Conclusions**

646 The integrated analysis of geophysical and sedimentological data collected on the narrow shelf off
647 the Antas and Almanzora Rivers in southern Iberia allowed us to decipher the Holocene morpho-
648 stratigraphic evolution of a compound submarine deltaic system and constrain the variability of
649 sediment transport processes during the last sea level rise. Three different evolutionary stages were
650 reconstructed, allowing us to map a larger submarine deltaic body with respect to its present-day
651 morphological expression. This has implications for the proper classification of deltaic bodies linked
652 with short and steep rivers that is currently based mainly on morphological criteria.

653 At present, the morphology and sedimentology of the shelf is controlled by the interplay between
654 riverine and marine processes. During flash flood events that have commonly affected the Almanzora
655 River, hyperpycnal flows are considered responsible for the formation of both a radial network of
656 gullies and seafloor undulations over the Almanzora prodelta slope, as supported by sandy samples
657 with high terrigenous content (mainly quartz and micas). A marked break-in-slope associated with
658 shelf-indenting canyon heads promotes ignition and erosion of these flows, first forming coaxial
659 trains of upper-flow regime bedforms and then strongly incised gullies. These latter are also affected
660 by pockmarks and small slide scars, indicating complex feedback between sedimentary gravity flows,
661 fluid seepage and retrogressive slope failures in the area. Marine processes are responsible for riverine
662 plume deflection, resuspension, and transport of fine-grained sediment in the mid-shelf, feeding
663 underlying tributaries of Garrucha canyon, as supported by silt-dominated sediments with high
664 terrigenous content.

665 In summary, the present study provides insights for a better understanding of sediment dispersal
666 linked with steep and mountainous river courses and its interaction with rugged paleo-topography
667 and shelf currents, which is particularly important for source-to-sink studies of shelf-incising canyons
668 affecting narrow shelf rimming tectonically controlled coasts. It is also noteworthy that similar coastal
669 areas are often strongly exploited by human settlements, especially along the Mediterranean Sea,
670 making the understanding of riverine flow dynamics and the evaluation of their impact on the marine
671 environment fundamental for assessing the associated hazards.

672

673 **Acknowledgements**

674 This research was supported by the Spanish Fauces project (CTM2015-65461-C2-1-R). We thank
675 IHS for providing the Kingdom Suite™ licence. We are also grateful for the technical support of

IGME during the use of the SEM located in their laboratories. The project “Torno Subito” (Regione Lazio) is acknowledged for providing a fellowship to Maddalena Biancone for her research period in the IGME (Spain). We also gratefully acknowledge two anonymous reviewers for the fruitful suggestions that have improved the quality of the paper.

Declaration of competing interest

The authors declare no competing financial interests.

Data availability

Casas, D., & UTM-CSIC. (2018). FAUCES-2 Cruise, RV Sarmiento de Gamboa [Dataset]. UTM-CSIC. <https://doi.org/10.20351/29SG20181004>

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Captions

Figure 1 a) Simplified morpho-structural sketch of the Palomares margin and nearby areas in the Gulf of Vera (SE Iberia, location in the inset), modified from Ercilla et al. (2019) CF: Carboneras fault, MF: Moreras fault, PF: Palomares fault. **b)** Shaded relief map and isobaths (dashed blue lines) of the Palomares margin encompassing the Aguas and Almanzora Rivers (location in the black box of Fig. 1a), with the location of the entire dataset of seismic profiles available for this study (thin black lines), selected seismic profiles (thick dashed lines) shown in Fig. 5 and seafloor samplings (yellow dots) (Figs. 7a and 9a, Table 1). Onland topography derived from lidar data gridded at 5 m resolution, freely downloadable from the Spanish National Geographic Institute (<http://centrodedescargas.cnig.es/>)

1067 **Figure 2** Shaded relief map and isobaths (equidistance of 10 m) **(a)** and slope gradient map **(b)** of the
1068 continental shelf encompassing the Antas and Almanzora Rivers (location in Fig. 1b). The shelf can
1069 be divided into three sectors, the southern (SS), central (CS) and northern (NS) shelf, which are
1070 characterized by different morphological features and bathymetric cross-sections (BC1-BC3) (V.E.:
1071 vertical exaggeration, 15x). One of the main morphological features is the deltaic body developed off
1072 the Almanzora River mouth in the central shelf; it can be divided into two convex-seaward areas
1073 (labelled A and B) characterized by cross-shelf gullies and seafloor undulations. BC4 and BC5 are
1074 cross-sections of the gullies shown in Fig. 4

1075 **Figure 3** a) Interpretative map of the main geomorphic features recognized on the shelf between the
1076 Antas and Almanzora Rivers (location in Fig. 1b); see text for details.

1077 **Figure 4** Close-up of the box in Fig. 2a showing different types of gullies, seafloor undulations,
1078 crescent-shaped bedforms (CSBs), pockmarks and small slide scars. Bathymetric profiles (BC4-10)
1079 of selected features are shown below and in the right panels. The location of the profiles is indicated
1080 by the blue dashed line in the main figure for BC6-10 and Figure 2a for BC4-5. V.E.: vertical
1081 exaggeration.

1082 **Figure 5** Seismic profiles (location in Fig. 1b) showing the seismo-stratigraphy of the shelf; note the
1083 presence of a high-amplitude and irregular basal reflector (BR) dividing the upper seismic unit U1
1084 from the lower unit U2. In the dip section, the BR truncates barely recognizable clinoforms of U2
1085 (indicated by arrows in Figs. e and f). U1 is divided into three sub-units, U1a, U1b and U1c, according
1086 to the seismic facies; the light-blue line indicates the limit between U1a and U1b, while the yellow
1087 line shows the limit between U1b and U1c. Und: seafloor undulation observed on the Almanzora
1088 prodelta, P: pockmark.

1089 **Figure 6** a) Location of seismic profiles available for the study (the black lines are the trace of the
1090 profiles shown in Fig. 5) and used to compute the isochrones of the basal reflector (BR in Fig. 5) and
1091 the thickness of the overlying Holocene seismic unit U1 (Fig. 5). b) Isochrones of the basal reflector
1092 in milliseconds (ms, two-way travel time). c) Isopach map of unit U1 expressed in metres (m) using
1093 a sound velocity of 1500 m/s for time/depth conversion.

1094 **Figure 7** a) Shaded relief map of the shelf off of the Almanzora River, with the 48 seafloor samples
1095 (see also Table 1) grouped by different ranges of mean grain sizes (μm). Note the progressive decrease
1096 in the mean grain size from the Almanzora fan towards the outer shelf and gullies/canyons indenting
1097 the shelf. b) Percentages of sand, silt and clay of the samples plotted on the Folk (1954) ternary
1098 diagram (see also Table 1ESM for the values).

1099 **Figure 8** SEM photos displaying terrigenous and biogenic components of the samples (a-f). a)
1100 Polymineralic rock fragment gathered from the DC31 sample composed of quartz (the dark crystals
1101 in the top left to top right part), Ti oxides (the light shaded portion) and micas (light grey). b) Broken
1102 foraminifera tests retrieved in DC49, referable to (from left to right) *Ammonia* sp., *Brizalina* cf.
1103 *spathulata* and a planktonic foraminifera fragment. c) Quartz crystal and Ilmenite grain from DC33.
1104 d) Another polymineralic rock fragment gathered from DC31 composed of diverse crystals: the
1105 lighter portion was identified as an Fe-bearing oxide, while the darker part is a Ca-carbonate. e)
1106 Muscovite lamina from DC43. f) Broken ostracod valve from DC15. For the sample location see Fig.
1107 6a and Table 1.
1108
1109

1110 **Figure 9 a)** Distribution map of the five classes of sediment identified by cluster analysis in the 36
1111 samples where grain size and compositional analyses of the sand fraction were performed. Group 1
1112 is sand-dominated and has the highest mean size and elevated terrigenous content. Group 2 is sand-
1113 dominated but has a lower mean size; the terrigenous content is high. Group 3 is silt-dominated and
1114 has a high terrigenous content. Group 4 is silt-dominated but is finer-grained than cluster 3 and shows
1115 a marked increase in biogenic content. Group 5 is silt-dominated, even though it has a higher mean
1116 size with respect to clusters 3 and 4; it shows the highest biogenic content among all the clusters. **b)**
1117 Graph showing the main factors defined by PCA, 3 of which explain 98.07% of the total variance
1118 (table in the upper right): component 1 (81.46% of the total variance) divides the samples into sand-
1119 dominated and silt-dominated samples. Component 2 (11.98% of the total variance) divides them in
1120 relation to the terrigenous and biogenic contents. Component 3 (4.63% of the total variance) is mainly
1121 linked to quartz and mica contents. **c)** Dendrogram used for dividing the 5 clusters.

1122
1123 **Figure 10** On the left, a simplified sketch showing the interaction between riverine and marine
1124 processes responsible for the formation of the Almanzora fan and the two main types of gullies
1125 recognized in the study area: deltaic-related and storm wave-related gullies (see also Fig. 3 and text
1126 for details). On the right, the graph shows the depth interval, the typical cross-section (vertical
1127 exaggeration of 10x) and the number of occurrences of the two types of gullies shown in the left
1128 image. Note that larger gullies (cross-section in black) include both (types 1 and 2) larger gullies
1129 developed within the canyon head.

1130
1131 **Figure 1 ESM** Zoom of the inner part of the southern shelf (location in Fig. 2a), morphologically
1132 characterized by a main break-in-slope (yellow line) corresponding to the edge of the infralittoral
1133 wedge (BC12), where a megaripple's field is recognizable (BC11).

1134
1135 **Table 1** Location and depths of the 48 samples analysed in this work. Colour refers to the different
1136 samples grouped according to their mean size as shown in Fig. 6 (yellow < 31 μm ; light blue 31-62
1137 μm ; blue 62-125 μm ; green 125-250 μm); * indicates the samples where compositional analysis of
1138 the sand fraction was not performed. For details on the grain-size analysis of each sample, refer to
1139 Table 1ESM.

1140
1141 **Table 2** shows the minimum, median and maximum values of depth and grain-size features of the
1142 48 samples shown in Fig. 7; for details on the grain-size analysis of each sample refer to the Table 1
1143 ESM.

1144
1145 **Table 3** Depth range and textural statistical parameters of the different granulometric fractions
1146 identified in the study area (Fig. 7) using the method of Folk and Ward (1957).

1147
1148 **Table 4** shows the minimum and maximum for the compositional and grain-size features of the
1149 samples belonging to the different clusters shown in Fig. 9a. For details on compositional and grain-
1150 size analysis of each sample refer to Table 2 ESM.

1151
1152 **Table 1 ESM** grain-size analysis of the 48 samples analysed in this study.

1153
1154 **Table 2 ESM** compositional and grain-size analysis of the selected 36 samples for the PCA.

Figure 1

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Figure 2

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Figure 3

Figure 4

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Figure 5

Figure 6

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Figure 7

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Figure 9

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Figure 10

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Table 1 Location and depths of the 48 samples analysed in this work. Colour refers to the different samples grouped according to their mean size as shown in Fig. 6 (yellow < 31 μm ; light blue 31-62 μm ; blue 62-125 μm ; green 125-250 μm); * indicates the samples where compositional analysis of the sand fraction was not performed. For details on the grain-size analysis of each sample, refer to Table 1ESM.

Sample	Easting (m)	Northing (m)	Depth (m)	Sample	Easting (m)	Northing (m)	Depth (m)
DC4	609088	4118307	56	DC8*	609801	4117836	106
DC45	609098	4116576	83	DC23	609925	4119396	55
DC5	609268	4118065	68	DC26*	610010	4119907	43
DC11*	609316	4118627	55	DC19	610534	4118545	99
DC6	609405	4117892	82	DC27*	610797	4119430	73
DC10*	609466	4118366	65	DC34	611435	4120652	65
DC7	609619	4117626	116	DC42	612235	4123652	54
DC47	609643	4116354	130	DC41	612705	4122588	57
DC22	609653	4119617	44	DC43	613312	4123502	64
DC9*	609707	4118112	86	DC14	608586	4118905	31
DC15	609933	4117335	177	DC13*	608854	4119208	32
DC48	609994	4116316	200	DC25*	609893	4119781	49
DC21	610201	4119098	73	DC30*	610192	4120407	38
DC20	610326	4118810	93	DC29*	610506	4120062	47
DC49	610425	4115641	293	DC28*	610748	4119782	57
DC18	610863	4118109	169	DC33	611105	4120843	52
DC17	611118	4117933	179	DC37	611331	4121903	43
DC16	611284	4117573	235	DC38	611347	4122571	42
DC50	613243	4121398	75	DC36	611787	4121823	50
DC3	608754	4118628	41	DC39	611839	4122574	50
DC44	608833	4116803	70	DC40	612269	4122572	55
DC12*	609128	4118885	45	DC35	612468	4121688	247
DC46	609230	4116473	93	DC31	610408	4121335	28
DC24	609445	4119796	35	DC32	610751	4121135	28

Table 2 shows the minimum, median and maximum values of depth and grain-size features of the 48 samples shown in Fig. 7; for details on the grain-size analysis of each sample refer to the Table 1 ESM.

	Depth	Sand%	Silt%	Clay%	Mean (µm)	Sorting (µm)	Skewness (µm)	Kurtosis (µm)
Minimum	28	8,91	11,72	0,57	14,8	2,05	-0,54	0,85
Median	60,5	37,99	56,13	5,44	38,09	3,08	-0,72	0,98
Maximum	293	87,71	85,59	11,22	166,3	3,96	0,1	2,16

Table 3 Depth range and textural statistical parameters of the different granulometric fractions identified in the study area (Fig. 7) using the method of Folk and Ward (1957).

Granulometric fraction	Depth (m)	Sorting (μm)	Skewness (μm)	Kurtosis (μm)
Medium-Fine Silt	44-293	2.5-4	-0.13-0.1	0.9-1
Coarse Silt	35-106	3-3.9	-0.31- -0.1	0.9-1
Very Fine Sand	31-247	2.4-3.3	-0.53- -0.37	1-1.57
Fine Sand	28	2-2.2	-0.4- -0.55	1.7-2.2

Table 4 shows the minimum and maximum for the compositional and grain-size features of the samples belonging to the different clusters shown in Fig. 9a. For details on compositional and grain-size analysis of each sample refer to Table 2 ESM.

Cluster	Biogenic %	Terrigenous %	Quartz %	Micas %	Heavy-weight %	Light-weight %	Others %	Rock Fragments %	Sand %	Silt %	Clay %	Mean (µm)	Sorting (µm)	Skewness (µm)	Kurtosis (µm)
1	2-7	93-98	25-40	17-42	5-20	14-24	2-5	0-4	62-87	12-35	1-3	64-166	2-3.3	-0.55 / -0.37	1-2.2
2	2-8	92-98	14-35	26-53	3-11	14-29	2-3	0-8	43-48	47-52	3-6	44-49	3-3.7	-0.3 / -0.1	0.9-1
3	3-14	86-97	19-33	26-51	4-10	14-22	1-6	0-8	13-35	58-80	5-9	17.8-34	2.8-3.8	-0.1/0.1	0.9-1
4	18-33	67-82	9-21	29-44	3-11	6-15	2-7	0-4	9-29	65-82	6-11	14.8-31	2.7-3.3	-0.17/0.1	0.95-1
5	22-37	63-78	13-16	21-34	4-12	13-19	2-6	0-4	26-44	51-64	5-10	24-41.6	3.5-4	-0.2/0.03	0.8-1

Conflicts of Interest: The authors declare no conflict of interest.